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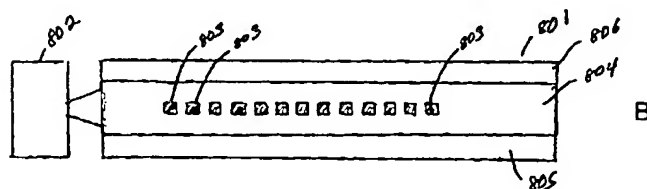
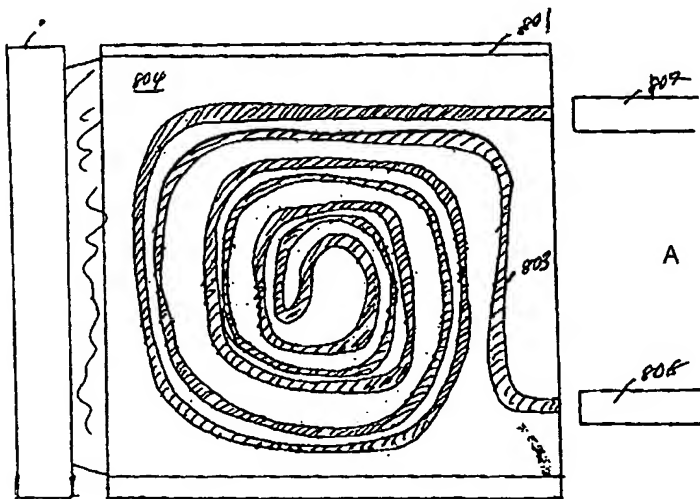
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(54) Title: OPTICALLY COUPLING INTO HIGHLY UNIFORM WAVEGUIDES



(57) Abstract: In accordance with the present invention, one or more laser diodes (802) are efficiently coupled into a waveguide amplifier (801) in order to provide either an efficient amplifier or a laser. Light from one or more laser diodes (802) is efficiently coupled into one or more waveguides (803) through the effects in the refractive index between the core material of the waveguide and the cladding material (804) around the waveguide. Both the core material (803) and the cladding material (804) can be deposited with a high degree of uniformity and control in order to obtain the coupling.



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## OPTICALLY COUPLING INTO HIGHLY UNIFORM WAVEGUIDES

### Background

#### 1. Technical Area

[0001] The present invention relates to coupling of pump light into an optical amplifier or a laser and, in particular, to coupling from a multimode laser diode in order to optically pump an optical amplifier or laser.

#### 2. Discussion of Related Art

[0002] Use of directed energy beams, such as those produced by amplifiers or lasers, are diverse and include applications in a wide range of fields, including biotechnology, medicine, semiconductor processing, manufacturing, image recording and defense. In biotechnology, directed energy beams are used, for example, in flow cytometry, DNA sequencing, confocal microscopy, and hematology. Medical applications include use in ophthalmology, non-invasive surgery, and photodynamic therapy. In the semiconductor industry, applications include wafer inspection, rapid thermal processing, and scribing or marking. Image recording applications include, for example, high-speed printing, photo-processing, film subtitling and holography. Industrial applications include, for example, rapid prototyping, materials processing and scribing or marking. Additionally, military applications include range finding, target designation, lidar, and chemical or biological threat detection. The graphics and printing industry, one of the largest businesses in the world, has a need for inexpensive laser systems for use in applications such as thermal graphics. Such applications require a highly reliable, low noise laser or optical amplifier at a low cost.

[0003] Typically, applications for directed energy beams require a laser or optical amplifier. An optical amplifier differs from a laser by the absence of a laser cavity. Both devices typically require an active optical material, for example rare-earth doped YAG, ruby ( $\text{Al}_2\text{O}_3:\text{Cr}$ ), or other material, which can be optically "pumped," such that energy can be stored in the excited states of the active atoms or molecules by an optical pump source. Amplification of input optical radiation or stimulated emission for lasing then occurs when the same optical energy stored in

the excited states is coupled to the incident optical beam.

[0004] Figure 1A shows an example of a side-pumped laser 100. Laser material 101 is positioned in a laser cavity defined by mirrors 102 and 103 and is pumped by diode array 104. Diode array 104 includes a series of laser diodes 105-1 through 105-N positioned to illuminate all or most of laser material 101. There are a variety of choices for laser diodes and laser diode arrays available to pump Nd or Yb doped YAG, for example. In most applications, Nd:YAG is pumped at about 808 nm and Yb:YAG is pumped at about 940 nm. Choices for diode array 104 include 10-40W arrays, 40-50W single bars, and 240-600W stacked bars, for example. Arrays can also be formed from readily available 1-2W single laser diodes.

[0005] Figure 1B illustrates the optical density in a cross section of laser material 101 in side-pumped laser 100 of Figure 1A. As is shown in Figure 1B, the optical density is greatest in the center of laser material 101 where the laser beam is located. However, much of the pump energy is dissipated in areas of laser material 101 that are not actively involved in the lasing process. Therefore, side pumping techniques are inherently inefficient.

[0006] As is illustrated in Figure 1A, the laser beam is directed between mirrors 102 and 103, where a percentage of the beam is transmitted through mirror 103. Figure 2 illustrates the shape of a laser beam in a laser cavity such as in laser 100. The closer the laser beam is to its diffraction limit in laser material 101, the greater the depth of field and the smaller the diameter of beam handling optics (for example mirrors 102 and 103) required to transmit the beam. The ratio of the divergence of the laser beam to that of a theoretically diffraction limited beam of the same waist size in the TEM<sub>00</sub> mode is usually given as  $M^2 = (\Theta/\theta)$ , where  $\Theta$  is the divergence angle of the laser beam and  $\theta$  is the divergence angle of the theoretical laser beam. The angular size of the laser beam in the far field will be  $M^2$  times the size calculated for a perfect Gaussian beam, i.e.  $\Theta = M^2(2\lambda/W_0)$  for a beam waist diameter of  $2W_0$ .

[0007] Figure 1C illustrates an end-pumping arrangement for pumping laser material 101. In the arrangement shown in Figure 1C, laser material 101 is again placed in a laser cavity formed by mirrors 102 and 103. The laser optical energy transmitted through mirror 103 is reflected by a dichroic beam splitter 114 to form the beam. Optical energy from pump source 116 is incident on lens 115 and passes through dichroic beam splitter 114 and mirror 103 to focus in a nearly diffraction limited region of laser material 101. The beam from pump source 116 is reduced to a size and shape that resembles the shape of the laser beam shown in Figure 2

in active material 101. Additionally, a second pump source 110 can be focused by lens 113 through mirror 102 and into laser material 101. In some embodiments, additional optical energy can be coupled into laser material 101 from pump source 111 using a polarizing beam splitting cube 112, which transmits light from pump source 110 while reflecting light from pump source 111.

[0008] A cross section of laser material 101 illustrating optical power concentration is shown in Figure 1D. As can be seen in Figure 1D, nearly all of the pump power, as well as the laser beam, is focused in the active region of laser material 101, where the laser beam produced by laser 117 is produced.

[0009] As is pointed out in U.S. Patent 4,710,940 to D. L. Sipes, Jr, issued on December 1, 1987, to a first approximation, and not being limited by theory, the higher the pump power density the more efficient is the use of pump power. This concept is illustrated in the graphs shown in Figures 1E and 1F. Figure 1E shows the photon conversion efficiency (i.e., the number of pump photons versus the number of output laser light photons) with increasing mirror reflectivity at various input optical power densities. Higher mirror reflectivity increases the optical power density within the laser cavity. At higher pump power densities, higher efficiencies result. Figure 1F shows photon conversion efficiencies as a function of pump power for various spot sizes, which shows the same trend of higher efficiency with optical density as does the graph shown in Figure 1E. Spot size refers to the diameter of the optical pump in the optically active laser material.

[0010] Table I shows typical power usage and lifetime characteristics for a side pumped laser 100 as shown in Figure 1A, an end-pumped laser 117 as is shown in Figure 1C, and a lamp pumped laser. As expected, the diode end-pumped laser 117 has the greater efficiency. However, end-pumped laser systems have more optical components and therefore are difficult to align.

[0011] Typically, the optical beam from a laser diode outputs is highly asymmetric. Therefore, light from the diodes is difficult to couple into the active material, e.g. laser material 101, of an optical amplifier or a laser. However, as shown in Table I, the lifetimes, efficiency, and expense of various laser diode configurations make them very attractive as pump sources for optically active devices.

Table I

	Lamp Pumped	Diode End-Pumped	Diode Side-Pumped
Power to Pump Source	5000W	2.5W	50W
Power to Cooling System	500W	2.5 W	50W
Power from Pump Source	3500W	1.25W	20W
Single-Mode Power from Laser	10W	0.8W	10W
Wall-Plug Efficiency	0.2%	16%	10%
Cooling	Water	Free Air	Forced Air
Power Consumed/Output kW-hr	500 kW-hr	6.5 kW-hr	10 kW-hr
Cost of Light Source	\$200	\$400	\$1000
Lifetime of Light Source	200 hrs	20,000 hrs	10,000 hrs

[0012] Multimode laser diodes are highly desirable optical pump sources as they are inexpensive to manufacture and are capable of producing much higher power levels than single mode lasers. Multimode lasers are more reliable than single-mode lasers as they have lower output power densities reducing the risk of catastrophic facet damage, the primary cause of laser diode failure. However the light emitted by a multimode laser diode is very asymmetric. Typically, the laser diode emitting aperture has dimensions on the order of  $1\mu\text{m} \times 100\mu\text{m}$ . It is very difficult and costly to collect and couple light emitted by a multimode laser diode into the end facet of a single-mode optical waveguide or fiber.

[0013] Most conventional waveguide amplifiers and lasers include one or more waveguide cores doped with active elements, such as Er, Yb, Nd and Tm, and are designed such that the waveguide can support coaxially propagating single-mode output and pump light. The output power of a single-mode, single laser pumped amplifier or laser is often limited to about 20dBm (100mW) by the power levels of available single-mode pump lasers. Single-mode pump lasers require more precision manufacturing tolerances and are consequently more expensive to produce than multimode lasers. As a result complex and costly schemes are required to pump arrays of waveguide optical amplifiers and lasers. Pump light has to be distributed to each amplifier channel or laser element, requiring combinations of splitters, combiners, taps, monitors

and associated control electronics to effectively manage the distribution. Polarization sensitivity of waveguide elements further complicates the distribution process.

[0014] Therefore, there is a need for optical laser devices capable of efficiently coupling light from a laser diode into the active region of a laser cavity that is cost effective and reliable, and that produces high optical output power.

### Summary

[0015] In accordance with the present invention, an optical waveguide device that couples light from at least one laser diode into a high refractive index contrast slab waveguide is presented. In some embodiments, the high refractive index contrast slab waveguide includes a light duct in a horizontal plane in order to receive light from the at least one laser diode. In some embodiments, the high refractive index contrast slab waveguide includes a high refractive index active waveguide and an intermediate refractive index passive cladding.

[0016] In some embodiments, the high refractive index contrast slab waveguide is folded in a horizontal axis. In some embodiments, the intermediate passive cladding is thick enough in the vertical axis to capture a substantial amount of light from the at least one laser diode in the vertical direction. In some embodiments, light transmitted from the optical waveguide device is efficiently coupled into single mode optical fibers by mode size converters.

[0017] These and other aspects of the present invention are further described in the following figures.

### Short Description of the Figures

- [0018] Figures 1A and 1B illustrate a side-pumped solid-state laser.
- [0019] Figures 1C and 1D illustrate an end-pumped solid-state laser.
- [0020] Figures 1E and 1F show graphs illustrating higher pump efficiency with higher optical densities.
- [0021] Figure 2 illustrates the characteristics of a typical laser beam in a laser cavity.
- [0022] Figures 3A and 3B illustrate integration of photodetectors and laser diodes with planar waveguides.
- [0023] Figure 4 illustrates a butt-coupling technique for optically coupling between a laser diode and a waveguide.
- [0024] Figures 5A, 5B and 5C illustrate integrated coupling chips for coupling optical energy from a single mode laser diode chip.
- [0025] Figures 6A and 6B illustrate a coupling chip for coupling optical energy from a multi-mode laser diode array to a multi-mode optical fiber in accordance with the present invention.
- [0026] Figures 7A and 7B illustrate a coupling chip for coupling optical energy from a multi-mode laser diode array to a single mode optical fiber in accordance with the present invention.
- [0027] Figures 8A and 8B illustrate an embodiment of an amplifier chip according to the present invention.
- [0028] Figure 9 illustrates the optical materials utilized in waveguides according to the present invention.
- [0029] Figures 10A, 10B, and 10C illustrate an efficient mode size conversion for vertical



pumping of an amplifier core.

[0030] Figure 11 illustrates a monolithic array beam concentrator chip according to the present invention.

[0031] Figures 12A and 12B illustrate the mode images for two example waveguides according to the present invention.

[0032] Figure 13 illustrates a Vertical Cavity Surface Emitting Laser (VCSEL) pumped microchip laser according to the present invention.

### Detailed Description

[0033] Lasers and other light sources have great utility when able to produce high optical power densities. The speed and effectiveness of the interaction of laser power or energy with materials is in direct proportion to the brightness and intensity of the power or energy that the laser can deliver to the material. The highest brightness or intensity of a laser output beam is obtained when the beam is confined to the fundamental, lowest order transverse electromagnetic mode ( $TEM_{00}$ ). Therefore, single transverse mode is the highest brightness form of a laser's output, which is the laser's most desirable property.

[0034] In accordance with some embodiments of the present invention, a high refractive index contrast multimode slab waveguide of an appropriate design to collect and contain a high proportion of the light emitted by a single or multi-element multi-mode pump laser diode and efficiently couple that light into an assembly of actively doped single-mode waveguides embedded within the slab is presented. The light from the pump source, then, is efficiently coupled into one or more active regions through the effects of the differences in refractive index between the slab material of the waveguide and the cladding material around the slab. Both the slab material and the cladding material can be deposited with a high degree of uniformity and control in order to obtain the coupling. Further, the embedded active core material of the waveguide can also be manufactured with a high degree of uniformity and control.

[0035] In some embodiments of the invention, long, single-mode waveguides are folded many times to accommodate lengths greater than the dimensions of the pumped, encapsulating

multimode slab waveguide. The single-mode waveguide cores can be folded in such a manner as to optimize the effective absorption cross-section they present to the guided multimode pump light flux while minimizing losses due to bending experienced by propagating single-mode signal light. The efficiency of absorption of pump light from the multimode laser diodes by single-mode actively doped waveguide cores is a function of the ratio of the effective cross-section areas of the single-mode and multimode waveguides.

[0036] In some embodiments of the invention, the multimode slab waveguide itself is pumped. This effect can result in a slap light source.

[0037] In some embodiments, the dimension of the multimode slab waveguide enables conservation of high power densities of the light emitted by the pump laser diode elements, while not increasing the difficulty and reducing the effectiveness of direct coupling between the laser diodes and the edge facet of the slab waveguide. High pump power densities are particularly important for three-level active systems where natural ground state absorption must first be bleached out before gain can be achieved.

[0038] In some embodiments single-mode light emitted by the laser diode in its fast axis direction (i.e., the direction of larger laser beam divergence) is converted to multiple-mode light immediately after the light enters a slab waveguide, thereby limiting the return path for pump energy to the pump laser source. Such an arrangement increases the pumping efficiency because more light is available for pumping.

[0039] Lasing and optical amplification processes are processes of energy conversion. Energy is pumped into exciting active elements in the active material, where the energy is stored, from any energy source, commonly optical, which is capable of exciting the active elements. Energy stored in the excited active elements, then, is released when the excited active element is induced by a signal, such as when the active element is perturbed by presence of another photon, into releasing the energy in the form of an optical photon. For example, energy from the excited states of a laser material is released in a highly coherent form by stimulated emission. The efficiency of the conversion process is a key factor in determining the cost-effectiveness of a particular laser or optical amplification or conversion process.

[0040] Planar waveguide forms of optical amplifiers and lasers are desirable as they are very compact compared to other forms of optical amplifiers and lasers. In addition, a planar

waveguide form potentially allows the integration of diverse optical and electronic functions on, for example, silicon wafers which can be manufactured in high volumes and at low cost with processes commonly used in the semiconductor-industry. In addition to waveguides, slab emitters are desirable as efficient light sources.

[0041] Figure 3A, for example, illustrates integration of an optical waveguide 301 with a photodetector (PD) 302. Photodetector 302 is formed on semiconducting layer 305. An optical layer 303 is formed over photodiode 302 and waveguide 301 is formed on optical layer 303. Light traveling through waveguide 301 can be coupled onto photodetector 302 at coupler 306.

[0042] Figure 3B illustrates integration of pump laser diodes 310 with an active material waveguide 311. As shown in Figure 3B, laser waveguide 311 is formed on an optical layer 313. Optical layer 313 is formed over laser diodes 310, which are formed on semiconducting layer 312. In some embodiments, laser diodes 310 can be formed to the side of optical waveguide 311, over optical waveguide 311, or in any other orientation with respect to optical waveguide 311 that allows pumping of the active dopant ions of optical waveguide 311.

[0043] Figure 4 illustrates coupling of a laser diode chip 410 with a high refractive index contrast ( $\Delta n$ ) waveguide 411. The method of coupling illustrated in Figure 4 is referred to as "butt coupling," where laser diode 410 is a single-mode semiconductor laser diode output facet positioned to within about 5  $\mu\text{m}$  of high  $\Delta n$  rectangular waveguide 411 in order to correct for mode astigmatism, thereby reducing coupling loss. In some embodiments, about a 50% coupling can be achieved with this method utilizing uncoated facets. Unfortunately, customer demand is for greater than 80-85% coupling efficiency for laser diodes with complex, non-gaussian mode output profiles. Therefore, conventional butt-coupling techniques are not meeting customer demand.

[0044] Figure 5A illustrates a laser coupling chip 501 that couples light from a laser diode 506 to an optical fiber 507. Coupling chip 501 includes a waveguide 502 with an integrated photodiode 503 to allow for down-stream power monitoring. In some embodiments, photodiode 503 may couple about 0.02 dB to about 0.05 dB of the optical power in waveguide 502 to provide optical coupling. A dual-core mode size converter 504 can be formed in coupling chip 501 to optimize for efficient optical coupling to optical fiber 507. Dual-core mode size converter 504 can couple light to optical fiber with a coupling loss of about 0.25 dB. The resulting total loss of less than 1 dB in laser coupling chip 501 results in a greater than 80% coupling efficiency

between laser diode 506 and optical fiber 507. However, there remains the problem that the coupling efficiency between laser diode 506 and coupling chip 501 is less than 80%.

[0045] In some embodiments, coupling chip 501 can be formed on a millimeter-scale chip sized to fit a standard 14-pin butterfly package. Further, in order to achieve optimum coupling efficiencies, the slow-axis and fast-axis alignment between laser diode 506 and coupling chip 501 requires sub-micron positioning precision.

[0046] Figure 5B shows a single mode laser diode array coupler chip 508. Light from laser diode array 520 is coupled into waveguides 521, 522, 523, and 524. Waveguides 521, 522, 523 and 524 are each integrated with a photodetector 525, 526, 527, and 528, respectively, as is discussed above with regard to Figure 5A. Further, mode size converters 529, 530, 531, and 532 formed in waveguides 521, 522, 523, and 524, respectively, efficiently couple light into optical fibers 533, 534, 535, and 536, respectively. Light from diode array 520, then, is coupled through optical fibers 521, 522, 523, and 524 into optical fibers 533, 534, 535, and 536. Figure 5C shows a single mode laser diode array coupler chip 509 similar to diode array coupler chip 508 with a pitch size converter 540, which provides for closer packing of optical fibers 533, 534, 535, and 536.

[0047] Other pumping schemes are described, for example, in U.S. Patent 6,236,793, issued to Lawrence et al. on May 22, 2001; U.S. Patent 4,710,940, issued to Sipes; U.S. Patent 4,785,459 issued to Baer on November 15, 1988; and at Lawrence Livermore National Labs. In a system proposed by Lawrence, et al., the pump light is reflected into the active waveguide core by reflecting the pump beam from a prism. Signal power is then transmitted through the prism into the waveguide core. However, in this configuration alignment of the optics directing the pump power into the waveguide core for efficient pumping needs to be arranged such that the waist of the beam is incident on the waveguide core. This results in a large alignment problem for efficiently coupling the pump power into the waveguide core. The arrangement proposed by Sipes involves an array of laser diodes arranged along the corners of a pumping path, for example a zig-zag pattern, such that pump power from multiple laser diodes are coupled into an active waveguide. The arrangement proposed by Baer includes a side pumped active material block with zig-zagging of the signal beam, through the active material for maximum interaction.

[0048] Lawrence Livermore National Labs has proposed a high output Yb:YAG laser system that utilizes a diode bar stack and a lens duct that brings the pump light from the diode bar stack

into a Yb:YAG laser rod. About an 80% coupling efficiency can be achieved in this fashion. However, this solution requires a bulk laser rod and a large lens duct to direct light from the diode bar stack into the laser rod.

[0049] Some embodiments of the present invention can utilize multimode laser diodes in the form of single elements or arrays, to efficiently pump compact, single-mode, planar waveguide optical amplifiers, lasers, and slab devices, which can be integrated with other optical and electronic functions and manufactured inexpensively in high volumes with semiconductor industry techniques. As shown in **Figures 6A and 6B**, the output light from a multimode laser diode 610 is single-mode in the vertical plane (the fast axis) and multimode in the horizontal plane (the slow axis). Therefore, the output beam diverges very rapidly in the vertical axis (the fast axis) but slowly diverges in the horizontal plane (the slow axis).

[0050] **Figures 6A and 6B** illustrate coupling of light from a laser diode array into a planar waveguide in accordance with the present invention. As shown in **Figures 6A and 6B**, the light beam from multimode laser diode array 610 diverges less in the slow axis direction (shown in **Figure 6A**) than it does in the fast axis direction (shown in **Figure 6B**). The output beams from laser diode array 610 diverge more in the vertical axis (shown in **Figure 6B**) than in the horizontal axis (shown in **Figure 6A**). Embodiments of the present invention take advantage of the slow divergence in the horizontal axis to increase the optical density in high refractive index waveguide 612. Coupling chip 611 can include a large lens duct 613 to direct light into high refractive index waveguide 612. The material of waveguide 612 and lens duct 613 can be the same material and can be deposited and patterned on a substrate in the same series of processing steps. Light from waveguide 612 can then be coupled into multimode fiber 614.

[0051] A higher optical power density, then, can be achieved utilizing less expensive multimode laser diode bars, rather than single mode laser diode arrays, and coupling the optical output from multiple ones of the laser diodes in diode array 610 into waveguide 612. Higher coupling efficiency is achieved by utilizing a light duct 613 formed with waveguide 612. Further, the horizontal alignment between diode array 610 and coupling chip 611 is not critical, so long as the light beams are directed toward duct 613. As shown in **Figure 6B**, alignment in the vertical axis (i.e., the fast axis) is somewhat critical because of the large divergence of the light output from diode array 610 in that direction.

[0052] The pump light from the laser diode can be constrained within the confines of the

high  $\Delta n$  slab waveguide and therefore no critical alignment exists between the laser diode and the active waveguide, as would be true for conventional pumping configurations as has been discussed above. Further, there is no need to maintain single-mode propagation in the horizontal direction, as alignment tolerance are relaxed in the horizontal plane. In the vertical plane, a single optical mode can be excited to obtain maximum power density by using more precise alignment. When maximize power density is not required, the alignment tolerances in the vertical plane can also be relieved by using a thicker high refractive index contrast slab waveguide and allowing the light to propagate multimode in the vertical direction as well.

[0053] Figures 7A and 7B illustrate coupling utilizing a double-clad core. As shown in Figure 7A, light from one or more laser diodes 710 of multimode pump diode array 702 is coupled into waveguide 703 of coupling chip 701. Again, a lens duct 704 can be formed with waveguide 703 to direct light from laser diodes 710 in diode array 702 into waveguide 703. In coupling chip 701, light from waveguide 703 can be coupled into single-mode fiber 705.

[0054] Figure 7B shows a cross-section of waveguide 703. Waveguide 703 includes a single-mode core 706. Single-mode core 706 can be formed, for example, from rare-earth doped  $\text{Al}_2\text{O}_3$ ,  $\text{Y}_2\text{O}_3$ , or  $\text{TiO}_2$  to form a high refractive index core. Single-mode core 706 can be surrounded by a multi-mode cladding 707 having a lower refractive index than that of single-mode core 706, which can be formed from an intermediate refractive index contrast material such as  $\text{Al}_2\text{O}_3$  or  $\text{Y}_2\text{O}_3$ . In some embodiments, the dimensions of multi-mode cladding 707 can capture most or all of the light output from laser diode array 702. Waveguide 703 can be formed on, for example, a silica or aluminasilicate buffer layer 709 deposited on a substrate. A second buffer layer 708 can be formed over waveguide 703.

[0055] In this way, coupling chip 701 can provide efficient conversion of low optical power density light emitted from directly-coupled multimode laser diode bars to high optical power density. Where high-refractive index contrast core 706 is optically active, a laser can be formed by including a laser cavity, which can be formed by depositing mirrors on the ends of chip 701.

[0056] Very high optical-to-optical efficiencies (e.g., greater than 80%) can be achieved in coupling chip 701. For example, a multimode laser diode operating at a wavelength of 920 nm, is efficiently coupled into a single-mode output laser at about 1100 nm utilizing an active waveguide 706 formed from double-clad Yb-doped silica, for example.

[0057] Having efficiently coupled the multimode pump light into a high refractive index slab waveguide which is multimode in the horizontal plane and may or may not be single mode in the vertical plane, a single mode active waveguide located in the high refractive index portion of the slab will be efficiently pumped. Such active areas are shown, for example, in Figures 8A and 8B. In some embodiments, the active region of the waveguide can be "folded" or routed through many loops in order to increase the length of active material pumped and thereby increase the amplification in the waveguide.

[0058] An embodiment of a folded active region embedded within the large high refractive index slab is shown in Figures 8A and 8B. One skilled in the art will recognize that any appropriate configuration or routing of active area waveguide within the slab can be utilized. For example, zig-zag configurations may also be utilized in addition to the spiral configuration shown in Figure 8A. Additionally, linear arrays of active regions may be utilized.

[0059] Figure 8A shows the slow axis view (i.e., the horizontal view) and Figure 8B shows the fast-axis view (i.e., the vertical cross section) of an active waveguide amplifier or laser chip 801 pumped by a multimode laser diode array in accordance with the present invention. As shown in Figure 8A, a single mode high refractive index contrast core 803 is arranged on chip 801. Although a spiral arrangement is shown in Figure 8A, any arrangement that provides a long signal path between a single mode input fiber 807 and a single mode output fiber 808 can be implemented. Light output from laser diode array 802 is captured by an intermediate refractive index contrast cladding layer 804 in which the single-mode high refractive index contrast active waveguide 803 is embedded. Figure 8B shows a cross section of an area of chip 801 with multiple crossings of single-mode high refractive index contrast active waveguide 803. As an example, active waveguide 803 can be formed from Yb-doped  $\text{Al}_2\text{O}_3$ ,  $\text{Y}_2\text{O}_3$  or  $\text{TiO}_2$ . Intermediate refractive index contrast cladding 804 can be formed from  $\text{Al}_2\text{O}_3$  or  $\text{Y}_2\text{O}_3$ . In this arrangement, a high pump-power density can be achieved in multi-mode cladding 804, which results in highly efficient pumping of active waveguide 803.

[0060] Multi-port amplifiers can be obtained by routing multiple folded regions of active waveguide such as waveguide 803 within the high  $\Delta n$  slab 804 of chip 801. For example, multiple active cores may be routed together as shown in Figure 8A. A single multimode pump, therefore, can be shared among several single-mode active amplifying waveguides without the need to split the pump light and separately distribute the light to activate the single-mode

amplifying waveguides separately. There is, therefore, no need for pump splitters or multiplexers. Further, the higher area of the active region increases absorption of the pump light, reducing the need for mirrors to rout the pump light through the active regions multiple times.

[0061] Figure 9 illustrates material depositions that provide high grade, optically transparent, highly uniform slab waveguides with highly controllable  $\Delta n$  values. The production of such waveguides is further discussed in U.S. Application Serial No. 09/903081, "As-Deposited Optical Waveguides with Low Scattering Loss and Methods for Their Manufacture," by Demaray et al, filed on July 10, 2001; U.S. Application Serial No. 10/101863, "Biased Pulse DC Sputtering of Oxide Films, by Zhang et al., filed on March 16, 2002; U.S. Application Serial No. 10/101,341, "Rare-Earth Pre-Alloyed PVD Targets for Dielectric Planar Applications," by Milonopoulou et al., filed on March 16, 2002; and Application Serial No. 09/633307, "Planar Optical Devices and Methods for their Manufacture," by Demaray et al., filed on August 7, 2000, each of which is incorporated by reference herein in its entirety.

[0062] Waveguide materials used to form active core waveguides, passive waveguides, and claddings consistent with embodiments of the present invention can be deposited by biased pulsed DC plasma vapor deposition (PVD), as described in U.S. Application Serial No. 10/101,341 (the '341 application). The physical characteristics of the optical material deposited by biased pulsed DC PVD depends on various process parameters, as discussed in the '341 application. A device, including photodetectors and other electronics, such as those shown in Figures 3A through 8B and discussed above, can be fabricated by depositing one or more active or passive optical layers and patterning the optical layers to form the waveguides and lens ducts as shown. In some applications, several deposition and patterning steps may be applied to form the desired structures.

[0063] As shown in Figure 9, which shows active and passive waveguide materials of highly amorphous, defect free films of aluminasilicated deposited by biased pulsed DC PVD. Further, the films have very high optical transparency, for example below 0.3 db/cm loss and, in some deposited films, less than about 0.1 db/cm loss. Therefore, deposition of films utilizing biased pulsed-DC PVD are useful for providing structures for optical coupling devices, optical amplifiers, and optical laser structures for highly efficient coupling of pump sources as has been discussed above.

[0064] In biased pulsed DC PVD, deposition is performed in a vacuum deposition chamber.



A substrate is mounted on a support which also provides an RF bias voltage to the substrate. RF power is supplied to a target formed from material to be deposited as gas is allowed into the chamber. A plasma is excited in the gas and the material is deposited on the substrate. Further, a pulsed DC signal is provided to the target. Further details regarding the deposition process are provided in the '341 application.

[0065] Coupling of light, for example from optical fiber 807 into waveguide 803, through efficient mode size conversion is illustrated in Figures 10A, 10B, and 10C. Vertically tapered mode-size conversion is further discussed in U.S. Application Serial No. 10/101492, "Mode Size Converter for a Planar Waveguide," by Tao et al, filed on March 16, 2002, herein incorporated by reference in its entirety. A very smooth vertical taper can efficiently couple light from optical fiber 807 into high refractive index contrast, core waveguide 803 very efficiently. Figure 10B shows the mode size of an optical beam at a point where light enters waveguide 803. Figure 10B shows a significantly smaller mode size in the region of waveguide 803 after the adiabatic S-taper mode size converter 1001. Mode size converter 1001 can be produced in a biased pulsed-DC PVD process with a shadow mask.

[0066] Table II shows modeling of mode diameter at the output facet of a mode converter for various core/cladding refractive index contrasts  $\Delta n$ . The dimensions in Table II refer to the dimensions of the output facet of the rectangular mode converter.

Table II

$\Delta n$	1.0 $\mu\text{m}$ x 1.0 $\mu\text{m}$	1.5 $\mu\text{m}$ x 1.5 $\mu\text{m}$	2.0 $\mu\text{m}$ x 2.0 $\mu\text{m}$	2.5 $\mu\text{m}$ x 2.5 $\mu\text{m}$
0.43%	38 $\mu\text{m}$	35 $\mu\text{m}$	14 $\mu\text{m}$	6 $\mu\text{m}$
0.3%		36 $\mu\text{m}$	20 $\mu\text{m}$	16 $\mu\text{m}$
0.2%			32 $\mu\text{m}$	24 $\mu\text{m}$

[0067] Figure 11 illustrates an image concentrator 1101 for adiabatically compressing the diameter of the mode output by a passively Q-switched microchip laser array. Image concentrator 1101 employs a reverse taper 1106, such as that first disclosed in U.S. Application Serial No. 10/101492 to Tao et al. Reverse taper 1106 can be formed vertically and/or horizontally and thereby provides coupling into a smaller mode size. A further embodiment includes a pitch size conversion such as that illustrated in Figure 5C. Embodiments of the

invention enable the mode size and pitch size conversion of individually addressable microchip laser array, so as to be tailored to standard print pixel densities for use in direct printing and micromaching applications.

[0068] Image concentrator 1101 can include an addressable array pump bar 1102 which is capable of addressing and exciting individual pixels of a microchip bar 1103. Array pump bar 1102 includes an array of laser diodes which produce light when individually addressed. Microchip bar 1103, which provides amplification as was discussed in Figures 6-8. Beam concentrator chip 1104 can include light ducts or vertical tapers in order to collect a substantial amount of light from microchip bar 1103. Further, a vertical reverse taper 1106, as is described in U.S. Application Serial No. 10/101,492, allows for a compressed output mode. As shown in Figure 11, the mode of the beam output by beam concentrator chip 1104 is much smaller than the mode of the beam in microchip bar 1103. In some embodiments, a monolithic array beam concentrator chip can convert 50  $\mu\text{m}$  or 90  $\mu\text{m}$  diameter single mode spots from microchip bar 1103 into 20 to 25  $\mu\text{m}$  diameter spots.

[0069] Figures 12A and 12B show mode sizes for some weakly-confined mode propagation in waveguides. Figure 12A illustrates a 6.2  $\mu\text{m}$  mode diameter at the output facet of a 1.5  $\mu\text{m}$  x 3.5  $\mu\text{m}$  waveguide for 980 nm light with a refractive index contrast  $\Delta n$  between the core and the cladding of about 1%. Figure 12B illustrates a 7.6  $\mu\text{m}$  mode diameter at the output facet of a 1.25  $\mu\text{m}$  x 3.5  $\mu\text{m}$  waveguide for 980 nm light with a refractive index contrast of about 1%. As is shown in Figures 12A and 12B, the optical energy is concentrated in the center of the facet.

[0070] Table III illustrates facet damage considerations in a image concentrator such as image concentrator 1101 shown in Figure 11. Table III illustrates, for representative pixel densities, the mode size required, the distance between modes, and the resulting power density in image concentrator 1101. The value of 14.2 for power density shown for 2400 dpi pixel density exceeds the damage threshold of Quartz.

Table III

Pixel Density (dpi)	Mode Pitch/Mode Size	Power Density at Facet ( $\text{GWcm}^{-2}$ )	Collimation Distance ( $\mu\text{m}$ )
600	42	0.9	842
1200	21	3.6	210
2400	11	14.2	53

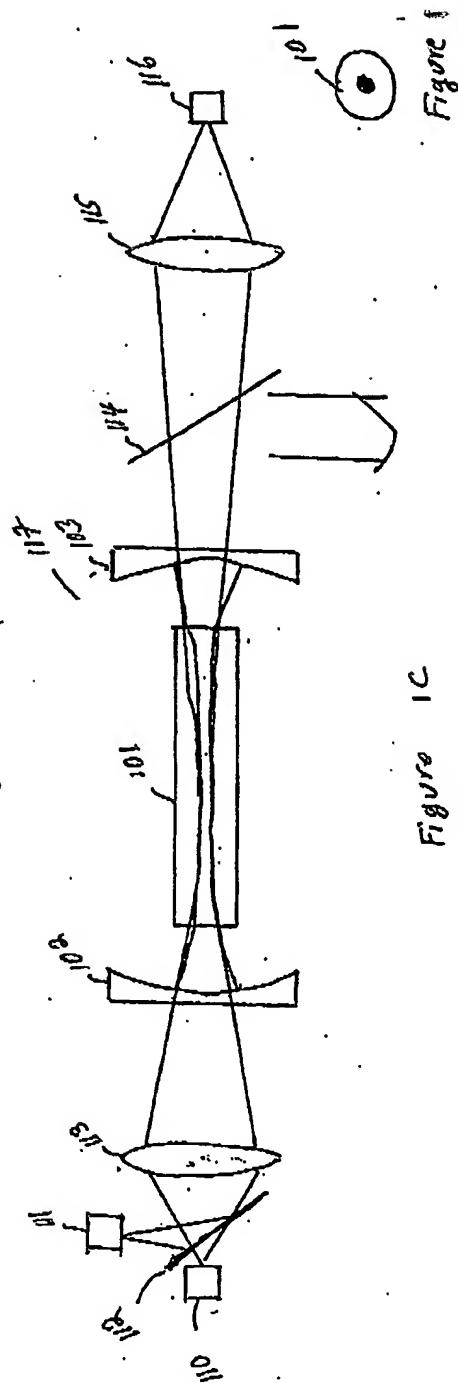
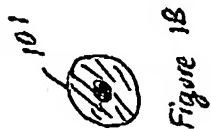
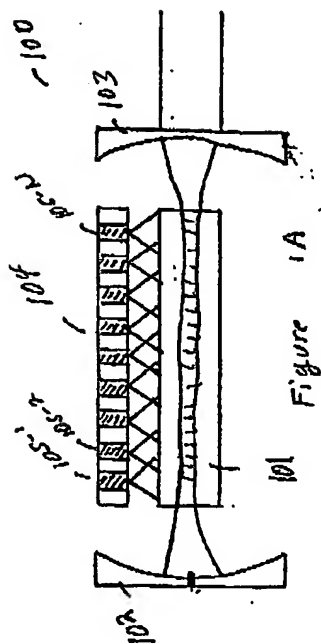
[0071] Figure 13 illustrates a vertical cavity surface emitting laser (VCSEL)-pumped microchip 1401 according to the present invention. VCSELs 1401 can be deposited on a GaAs substrate 1402. VCSELs 1401 include a dichroic output facet coating. An active gain medium 1404 can be deposited directly over VCSELs 1403. Active gain medium 1404 can be, for example, Nd, Yb, Er, Tm, Ho, Pr, or Ce doped silica. A saturable absorber 1405 can be deposited over gain medium 1404. Saturable absorber 1405 can be, for example, a Cr<sup>4+</sup> or Co<sup>2+</sup> doped silica film. A VCSEL pumped microchip 1401 can be fabricated using high volume wafer-scale semiconductor manufacturing techniques. The doped silica used for saturable absorber 1405 and active gain medium 1404, for example, can be deposited by biased pulsed-DC PVD processing techniques.

[0072] The embodiments discussed here are examples only and are not intended to be limiting of the invention. One skilled in the art will recognize multiple variations that are intended to be within the spirit and scope of the present disclosure.

I claim:

1. An optical waveguide device, comprising,  
  
at least one laser diode; and  
  
at least one high refractive index contrast slab waveguide coupled to receive light from the at least one laser diode,  
  
wherein the slab waveguide is deposited by biased pulsed DC plasma vapor deposition.
2. The optical waveguide device of claim 1, wherein the slab waveguide is formed from a highly amorphous film.
3. The optical waveguide device of claim 1, wherein the slab waveguide is highly optically transparent.
4. The optical waveguide device of claim 1, wherein the slab waveguide has a high surface smoothness.
5. The optical waveguide device of claim 1, wherein the high-refractive index contrast slab waveguide includes a lens duct.
6. The optical waveguide device of claim 1, wherein the at least one laser diode comprises a diode array.
7. The optical waveguide device of claim 1, wherein the high refractive index contrast slab waveguide includes a high refractive index active waveguide and an intermediate refractive index passive cladding.
8. The optical waveguide device of claim 7, wherein the high refractive index contrast slab waveguide is folded in the plane of the slab.
9. The optical waveguide device of claim 7, wherein the intermediate passive cladding is thick enough in the vertical axis to capture a substantial amount of light emitted from the at least one laser diode.
10. The optical waveguide device of claim 1, wherein the high refractive index contrast slab waveguide includes a mode-size converter.

11. The optical waveguide device of claim 1, wherein the at least one laser diode is a vertical cavity surface emitting laser and the high refractive index contrast waveguide is deposited over the vertical cavity surface emitting laser.
12. The optical waveguide device of claim 1, wherein the high refractive index contrast slab waveguide includes an array of waveguides.
13. The optical waveguide device of claim 11, wherein a mode size of an optical beam transmitted by the high refractive index contrast slab waveguide is less than a mode size of an incident optical beam.
14. The optical waveguide device of claim 12, wherein the high refractive index contrast slab waveguide includes at least one vertical reverse taper.
15. A method of coupling pump light into a gain medium, comprising:
  - depositing the gain medium by a biased pulsed-DC plasma vapor deposition process;
  - forming a high refractive index contrast waveguide from the gain medium; and
  - directing pump light into the high refractive index contrast waveguide.
16. The method of claim 15, wherein forming a high refractive index contrast waveguide includes patterning the gain medium.
17. The method of claim 16, further including depositing an intermediate refractive index contrast material over the high refractive index contrast waveguide.
18. The method of claim 16, wherein patterning the gain medium includes forming a lens duct.
19. The method of claim 16, wherein patterning the gain medium includes forming a horizontal taper.
20. The method of claim 16, wherein depositing the gain medium includes forming a vertical taper.



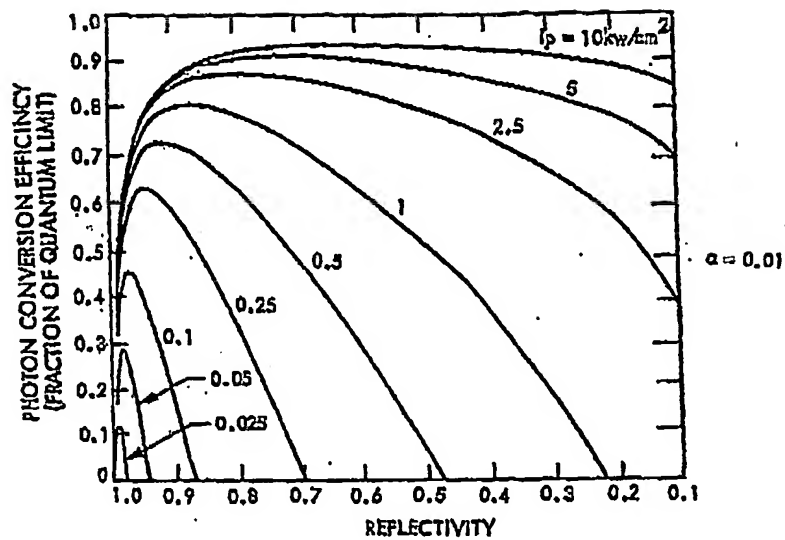


Figure 1E

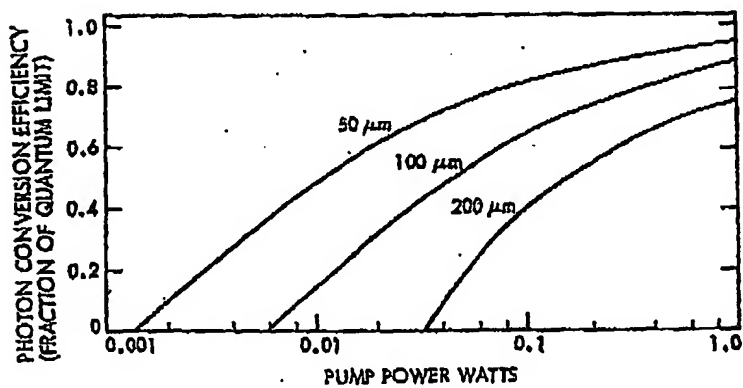
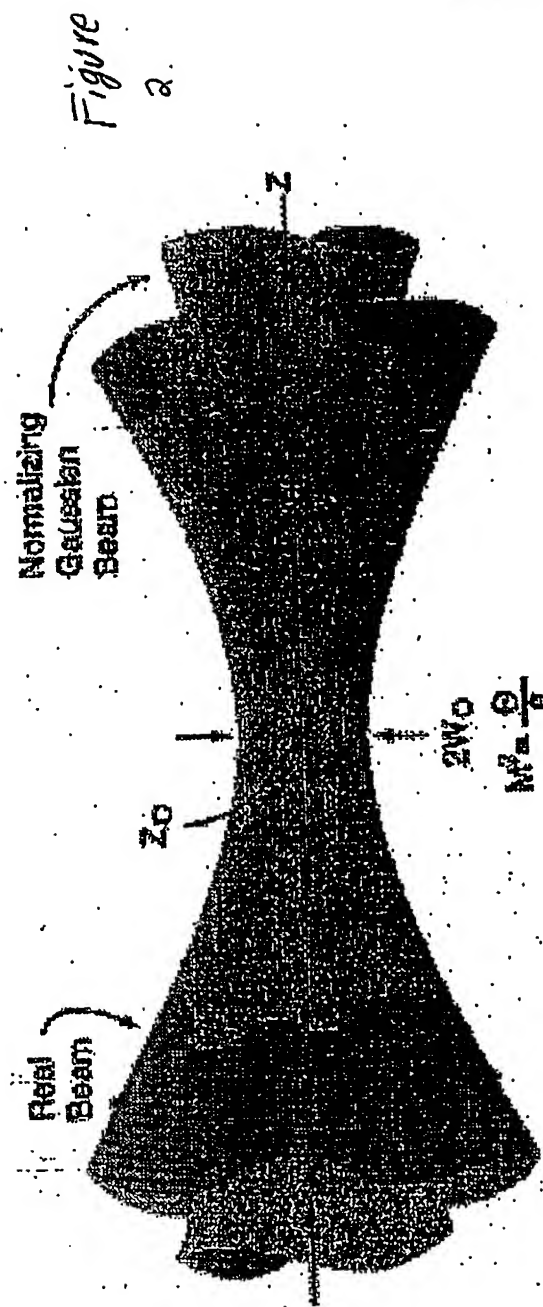


Figure 1F





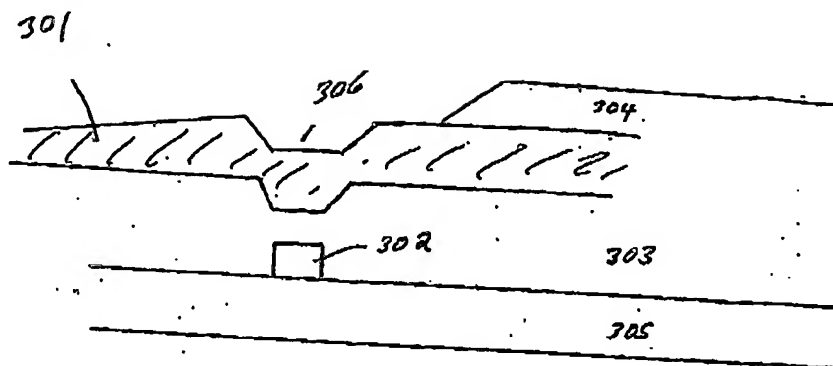


Figure 3A

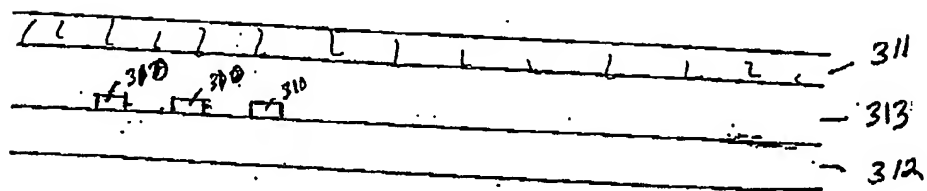


Figure 3B

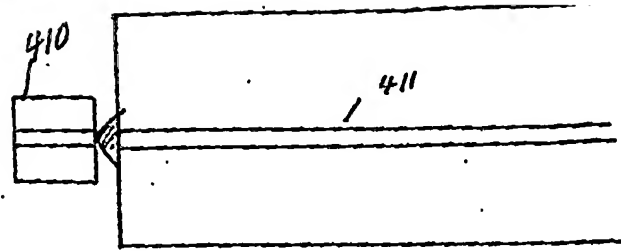


Figure 4

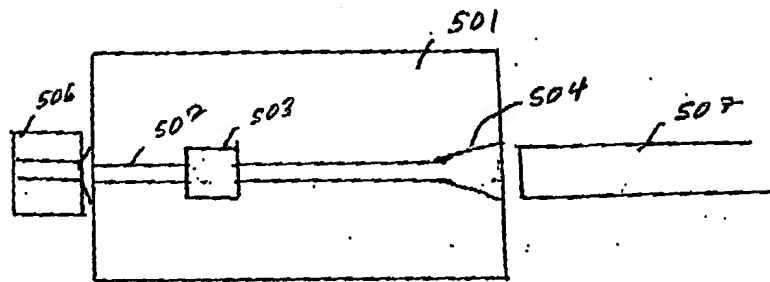


Figure 5A

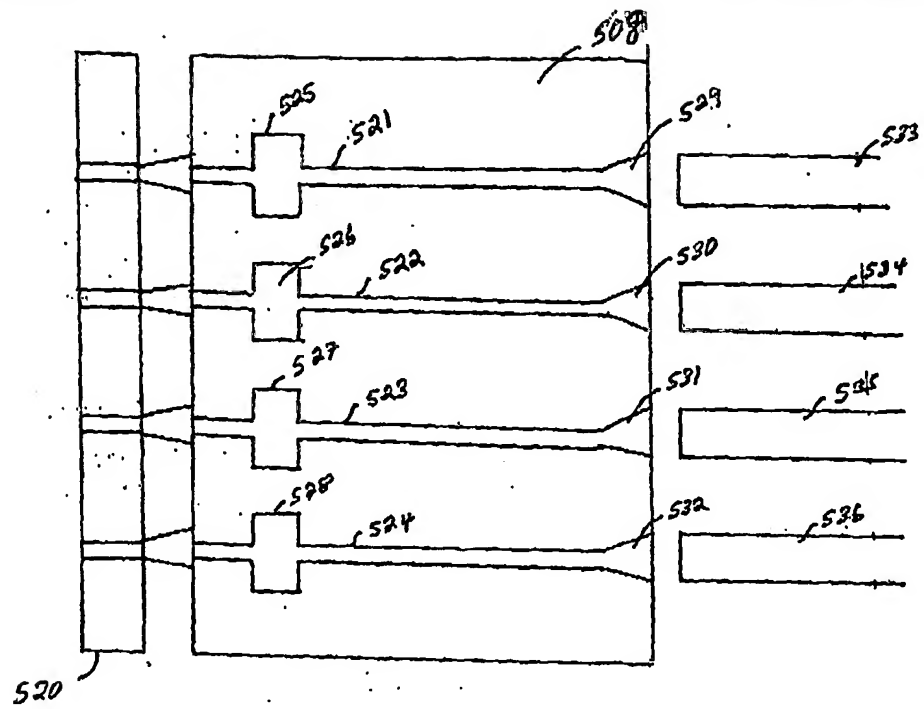


Figure 5B

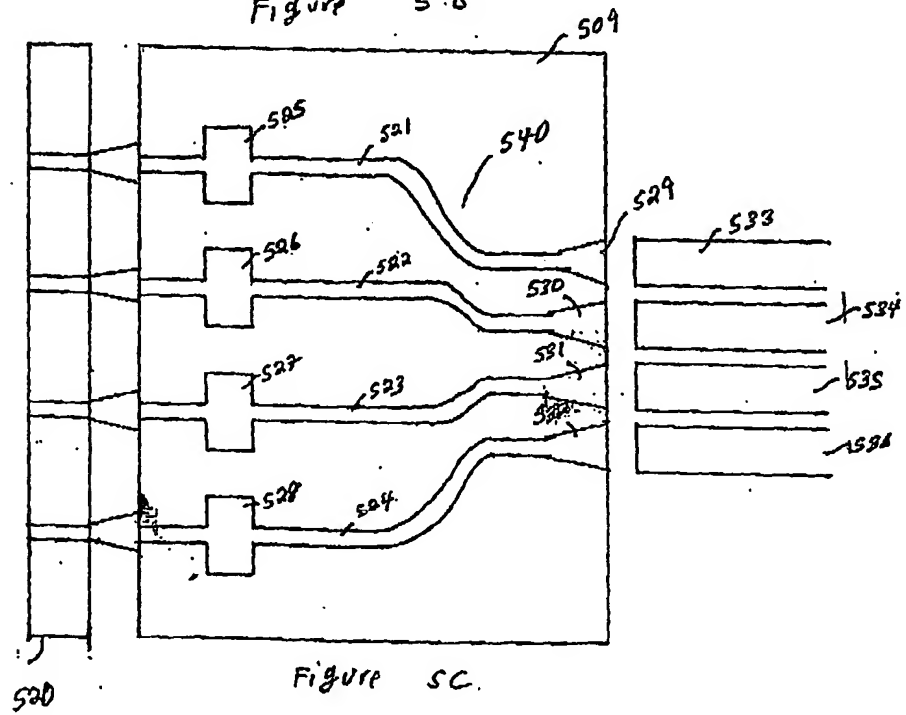


Figure 5C

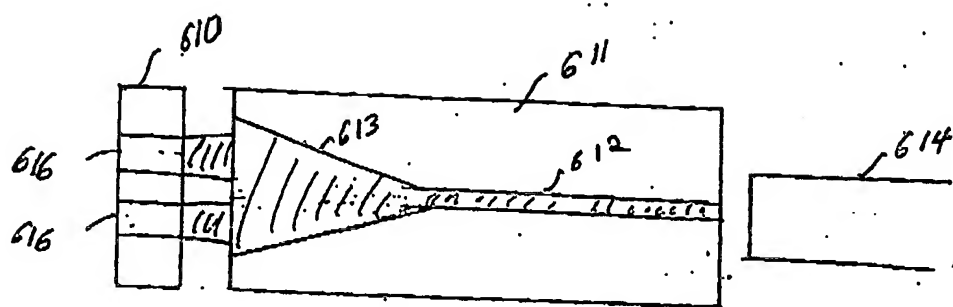


Figure 6A

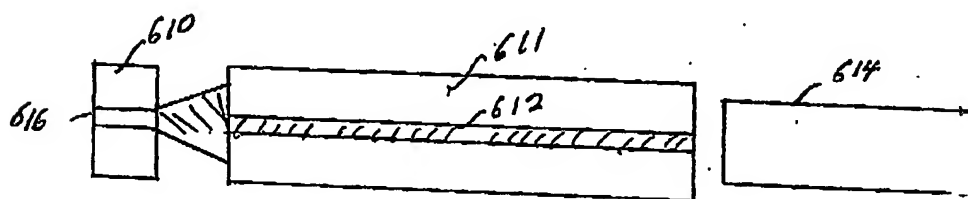


Figure 6B

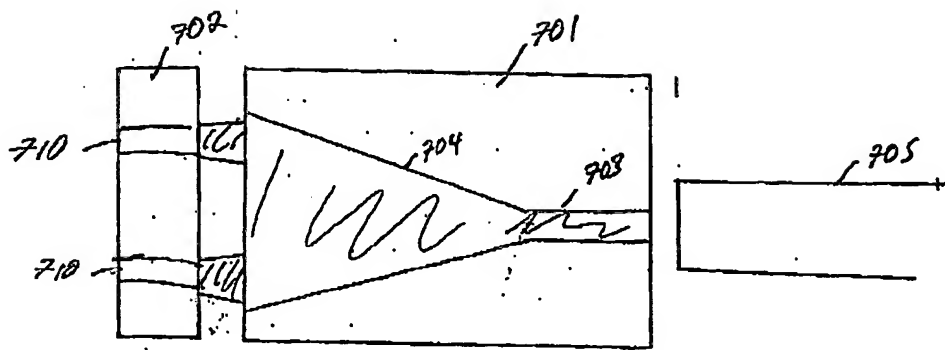


Figure 7A

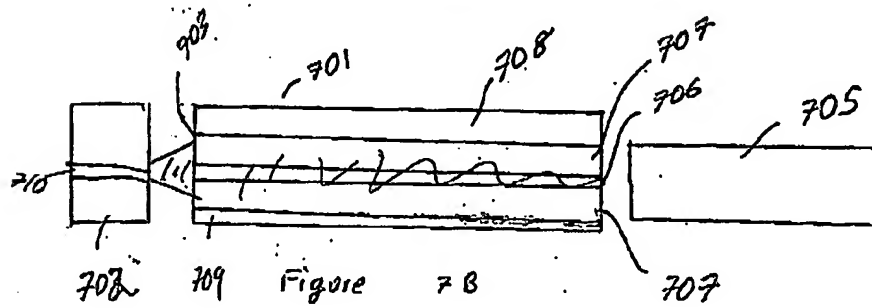


Figure 7B

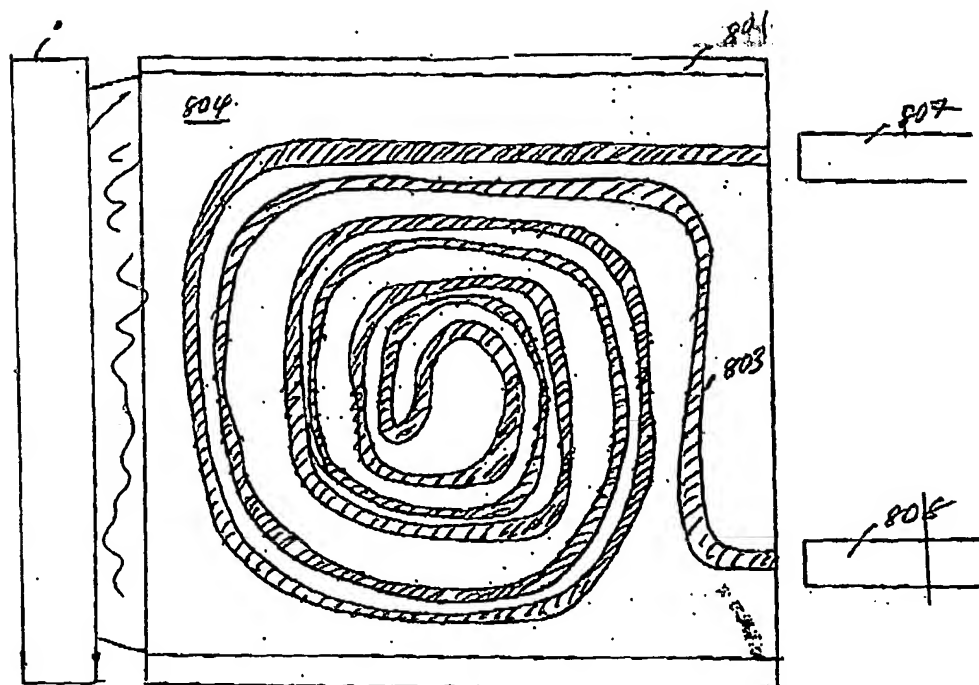


Figure 8A

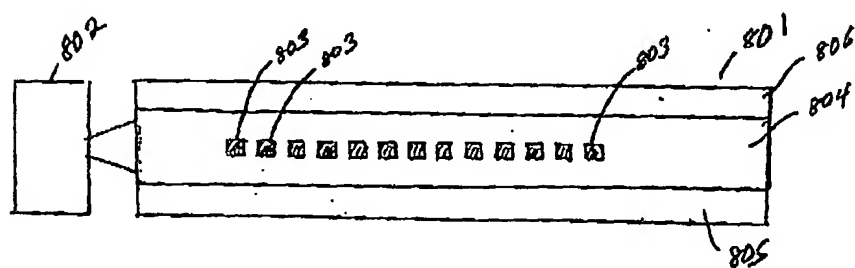
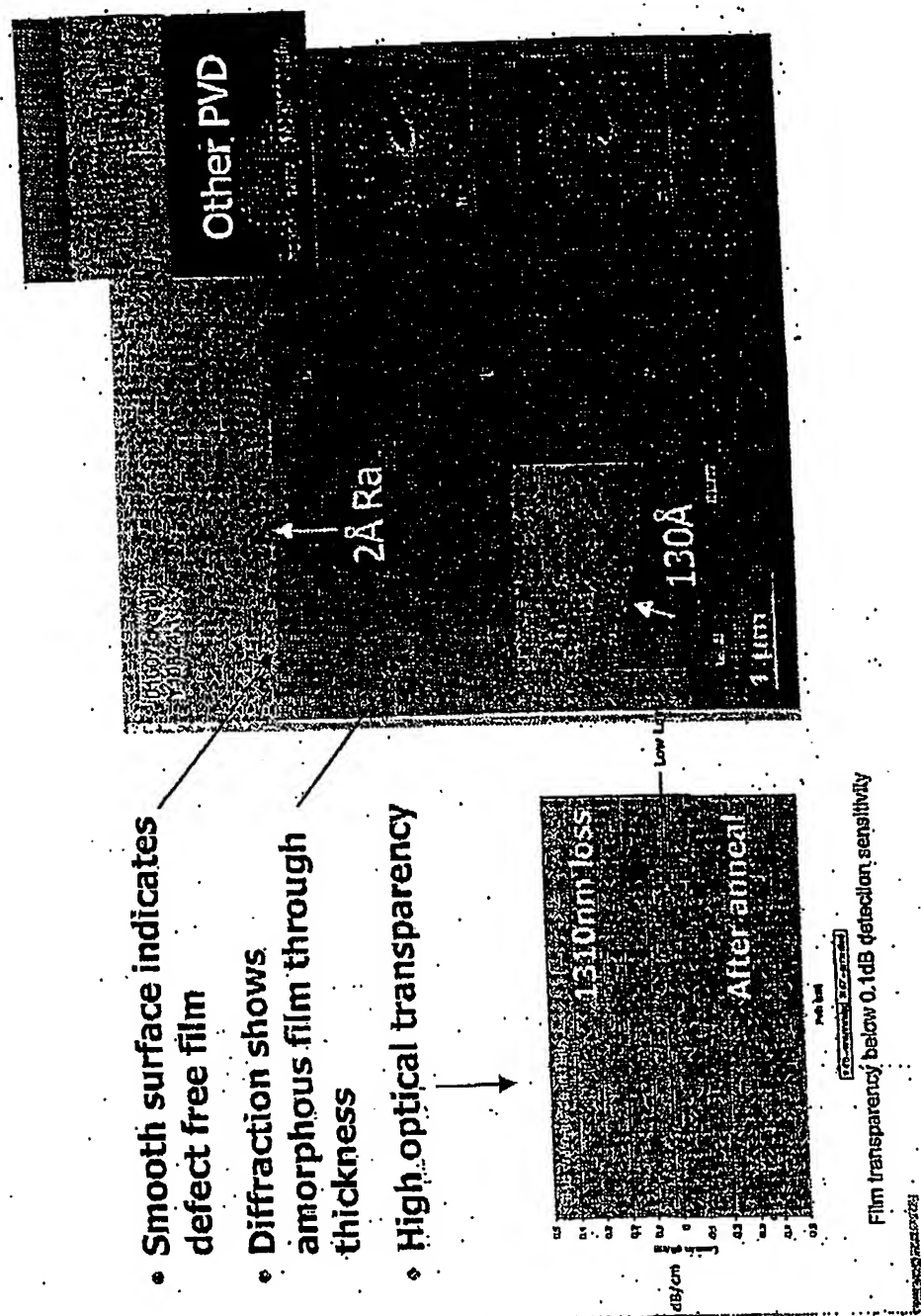


Figure 8B



- Smooth surface indicates defect free film
- Diffraction shows amorphous film through thickness
- High optical transparency

Figure 9

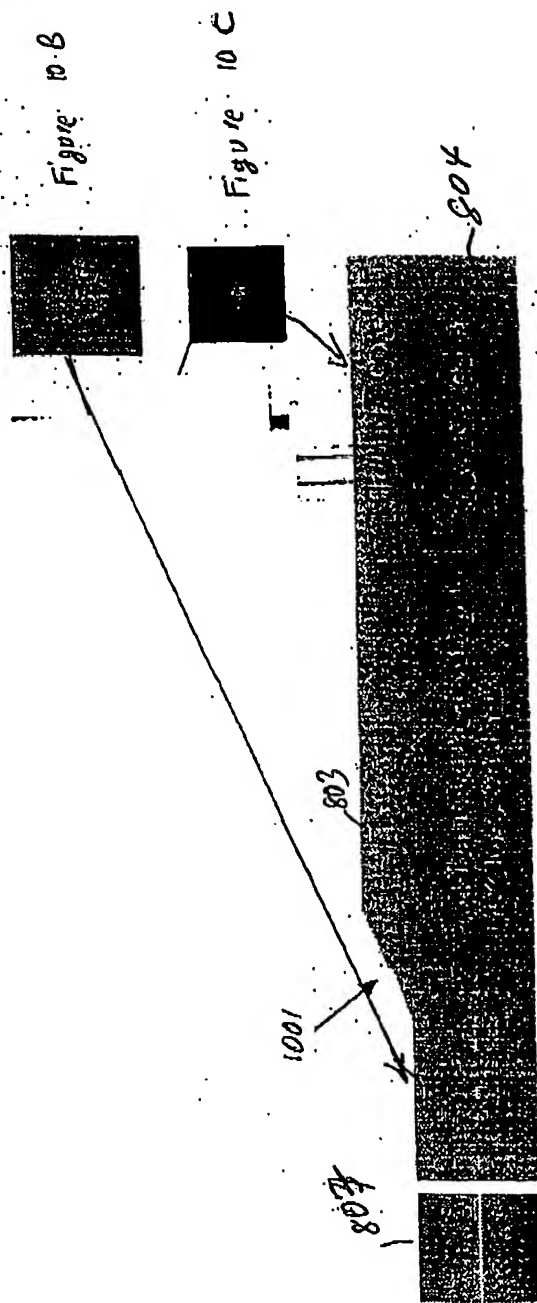
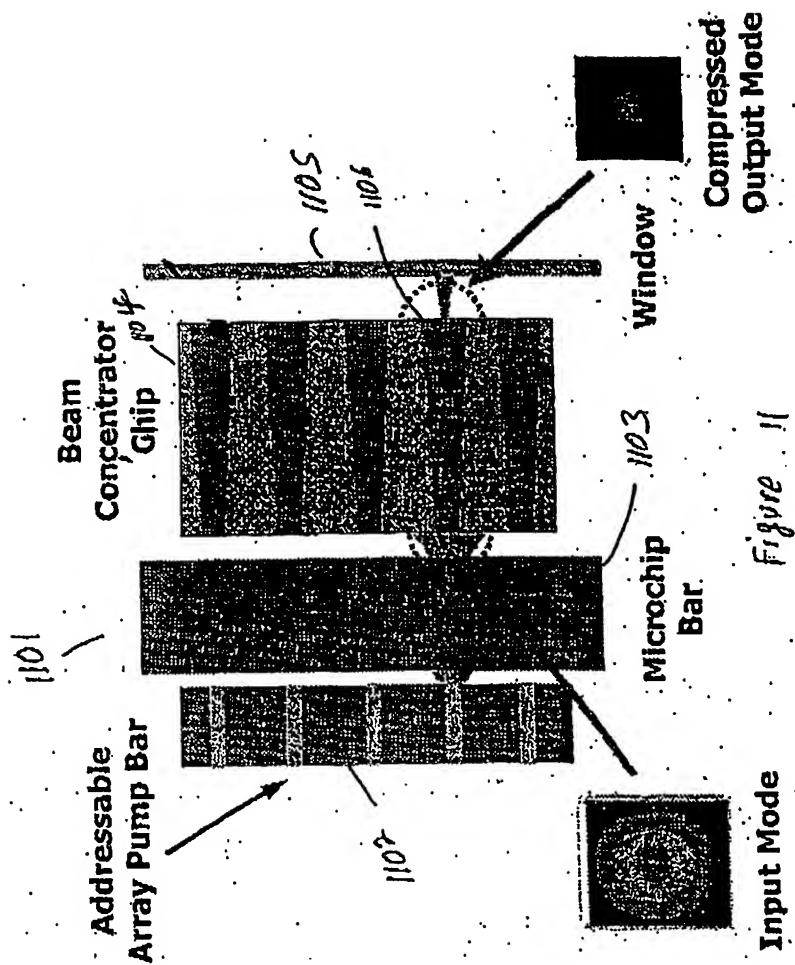


Figure 10A





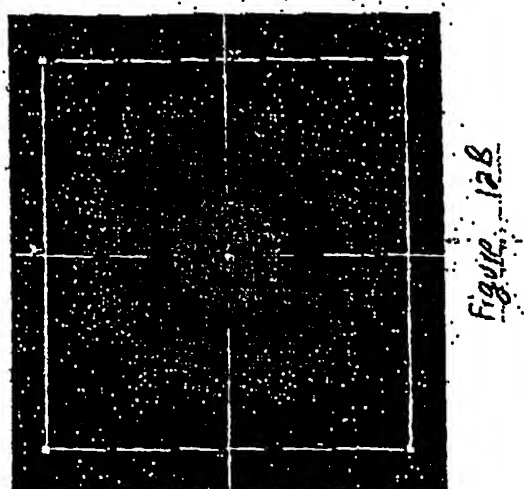


Figure 12B

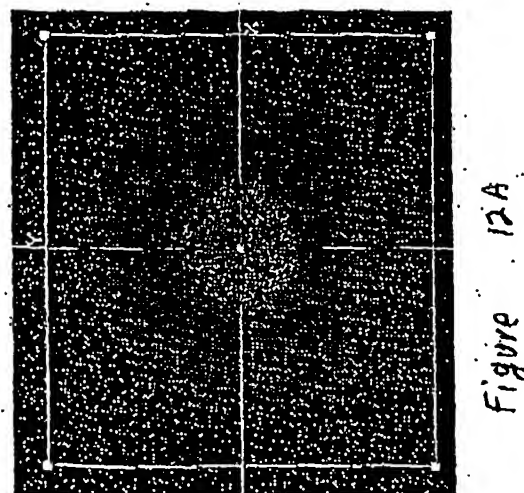


Figure 12A

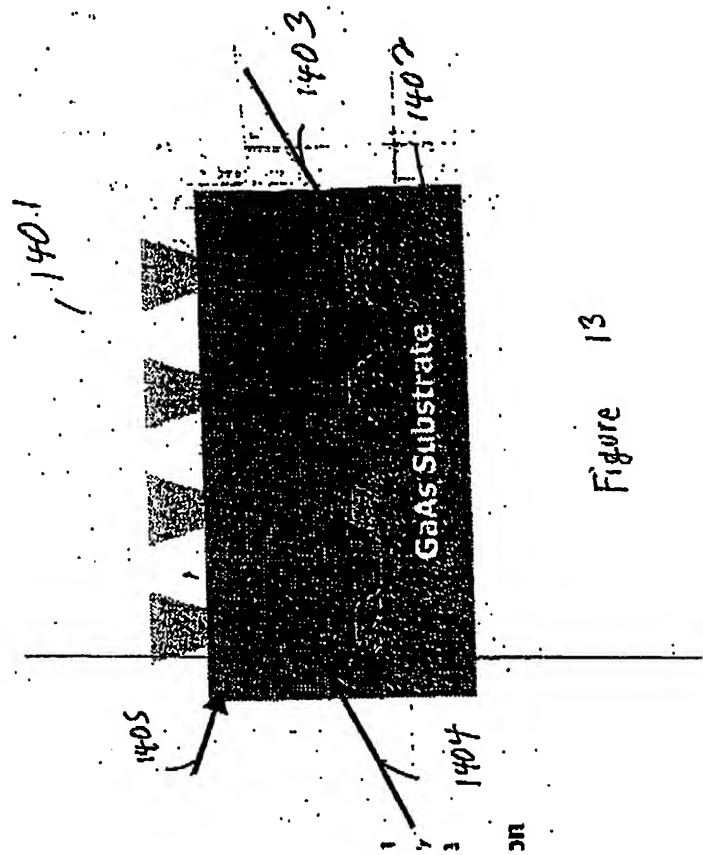


Figure 13

## INTERNATIONAL SEARCH REPORT

International Application No.

PCT/US 03/24809

A. CLASSIFICATION OF SUBJECT MATTER  
 IPC 7 H01S3/16 H01S3/063 H01S3/0933

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, WPI Data, PAJ

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 02 12932 A (SYMMORPHIX INC) 14 February 2002 (2002-02-14) cited in the application page 5, line 22-26; figure 5	1-20
A	JONSSON L B ET AL: "Frequency response in pulsed DC reactive sputtering processes" THIN SOLID FILMS, ELSEVIER-SEQUOIA S.A. LAUSANNE, CH, vol. 365, no. 1, April 2000 (2000-04), pages 43-48, XP004195125 ISSN: 0040-6090 paragraph '0001!	1,15
A	US 5 689 522 A (BEACH RAYMOND J) 18 November 1997 (1997-11-18) column 3, line 41-52	5,6,18
	-/-	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

21 November 2003

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## INTERNATIONAL SEARCH REPORT

International Publication No

PCT/US 03/24809

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 6 052 397 A (JEON HEON SU ET AL) 18 April 2000 (2000-04-18)  column 2, line 66 -column 3, line 4	10,11, 13,14, 19,20
A	BEACH R J: "Theory and optimization of lens ducts" APPLIED OPTICS, 20 APRIL 1996, OPT. SOC. AMERICA, USA, vol. 35, no. 12, pages 2005-2015, XP002262395 ISSN: 0003-6935 the whole document	5,6,18
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Information on patent family members

International Application No

PCT/US 03/24809

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US 6052397	A	18-04-2000	US 6174748 B1	16-01-2001
US 2003063883	A1	03-04-2003	NONE	